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LIQUEFACTION VULNERABILITY MODEL FOR URBAN AREAS

Alejandro Cruz [1,2], Nicola Chieffo[3], Shaghayegh Karimzadeh[1], Eimar Sandoval[2], Paulo B Lourenço[1]

[1]ISISE, Department of Civil Engineering, University of Minho
Campus de Azurém, Guimarães, 4880-058, Portugal
id10180@alunos.uminho.pt, shaghkn@civil.uminho.pt,
pbl@civil.uminho.pt

[2]G7, School of Civil Engineering and Geomatic, Universidad del Valle, Cali, Colombia
eimar.sandoval@correounivalle.edu.co

[3]Department of Engineering, School of Computing and Engineering, University of Huddersfield, Queensgate, Huddersfield HD1 3DH, UK
N.Chieffo@hud.ac.uk

Abstract

This paper presents a methodology to estimate liquefaction-induced damage in urban centres, utilizing well-established geotechnical, structural, and seismic indicators. The study employs the Vulnerability Index method, combined with the Analytic Hierarchy Process, to systematically evaluate and weigh key factors. This approach provides a comprehensive assessment of building vulnerability to liquefaction, with a particular focus on rigid-body displacement effects, especially in areas where a non-liquefiable layer overlays a liquefiable one.

Keywords: Liquefaction, Urban scale, Vulnerability index

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1 INTRODUCTION

Significant liquefaction-induced damage to the built environment has been documented in numerous major earthquakes, such as those in San Francisco (1906), Niigata (1964), Nihonkai-Chubu (1983), Hokkaido-Nansei-Oki (1993), Hyogoken-Nanbu (1995), Kocaeli (1999), Duzce (1999), Haiti (2010), Chile (2010), Tohoku (2011), and Kumamoto (2016) earthquakes [1]. These events underscore the need for models capable of assessing liquefaction-induced building damage at an urban scale, which are essential for risk mitigation in seismically active regions [2].

In the last decade, approaches focusing on liquefaction-induced building settlement (LIBS) have been instrumental in identifying key parameters that play a significant role in structural vulnerability assessments, particularly in relation to settlement. Foundation settlements are contingent on numerous factors, including but not limited to footing size, crust thickness, crust shear strength, residual strength of the liquefied layer, modulus of the liquefied layer, thickness of the liquefied layer, characteristics of earthquake shaking (duration, amplitude), time of liquefaction triggering, pore pressure mechanism, drainage, and more [3].

Recent advancements in LIBS modelling have emerged from various studies [4]–[6], among others, providing critical insights into the parameters that require precise definition or refinement to assess the impact of soil liquefaction on built environment vulnerability. These models offer the advantage of incorporating the most influential factors governing both capacity and demand, relying on sophisticated analytical frameworks [7]. However, for urban-scale seismic vulnerability assessments, simpler models are needed to facilitate the rapid identification of the most susceptible structures. This capability is crucial for prioritizing timely and effective strengthening interventions [8].

In this paper, a simplified methodology for estimating liquefaction-induced damage on liquefiable soils is proposed, adopting a different approach based on commonly known parameters, aligning with studies conducted at an urban scale. Multi-Criteria Decision Making (MCDM) methods are used to develop a vulnerability index ensuring robustness through expert judgment. The notable contribution of this research lies in the inclusion of parameters specifically associated with the vulnerability of the built environment to earthquake-induced liquefaction.

A holistic approach to modelling liquefaction-induced building damage considers two primary components: (i) damage caused by ground shaking alone (seismic vulnerability) and (ii) damage induced by liquefaction (liquefaction vulnerability). However, this study focuses exclusively on liquefaction vulnerability component. The separation of these components is feasible under the assumption that the two hazards do not interact, in which case affected buildings behave as rigid bodies [9]. This distinct damage mechanism, characterised by rigid-body displacements, excessive settlements, tilting, and, in extreme cases, complete overturning, was clearly observed in Gölbaşı following the Kahramanmaraş seismic sequence of February 6, 2023 [10].

To assess the physical vulnerability of the built environment to liquefaction, this study utilises the Vulnerability Index (VI) method, a widely recognised tool for engineers, policymakers, and urban planners [11]. A crucial step in developing VI is the systematic selection and evaluation of indicators. In this study, this process ensures the comprehensive integration of geotechnical and seismic factors, which influence both liquefaction occurrence (hazard) and the expected structural damage (vulnerability).

The objective is to establish a scientifically grounded framework for integrating liquefaction-induced damage into broader seismic vulnerability assessments at an urban scale. By improving the accuracy of liquefaction damage models, this research contributes to urban risk assessments, supporting disaster resilience strategies and mitigation planning.

The paper is structured as follows: Section 2 outlines the proposed methodology, detailing key components of the liquefaction vulnerability model and its validation approach. Section 3 presents the case study implementation. Finally, Section 4 summarizes the key advantages, discusses challenges, and suggests directions for future research.

2 PROPOSED METHODOLOGY

To assess liquefaction vulnerability at an urban scale, this study leverages previously reported data and geospatial information to identify key indicators and analyse their impact on the built environment. The problem is divided into two main components: (i) seismic and geotechnical, including geological soil properties and dynamic parameters, which accounts for earthquake characteristics and liquefaction indicators; (ii) structural, which involves rapid visual screening of buildings.

The proposed methodology consists of five key steps: (i) development of a Liquefaction Hazard Index (LHI), using Liquefaction Manifestation Severity Indicators (LMSI), including the Liquefaction Potential Index (LPI), Ishihara-inspired LPI (LPI_{ISH}), and Liquefaction Severity Number (LSN), combined with geotechnical and earthquake parameters such as crust thickness (H_1), liquefiable thickness (H_2), groundwater table (GWT) depth, earthquake magnitude (M_w) and peak ground acceleration (PGA); (ii) assessment of structural vulnerability, using rapid visual screening parameters to determine a Vulnerability Index for the structural component (VIS); (iii) integration of the VIS with the LHI to establish a final Vulnerability Index (VIF); (iv) classification of urban areas into vulnerability zones based on VIF.

The VIS includes both structural and geotechnical parameters. While geotechnical factors enhance the LHI, they also influence structural vulnerability by interacting with the building's condition. This dual role of geotechnical parameters is crucial in assessing the overall vulnerability to liquefaction. The following section provides a detailed breakdown of the methodology, while Fig. 1 shows the procedure for determining the VIF by combining LHI and VIS both using the AHP.

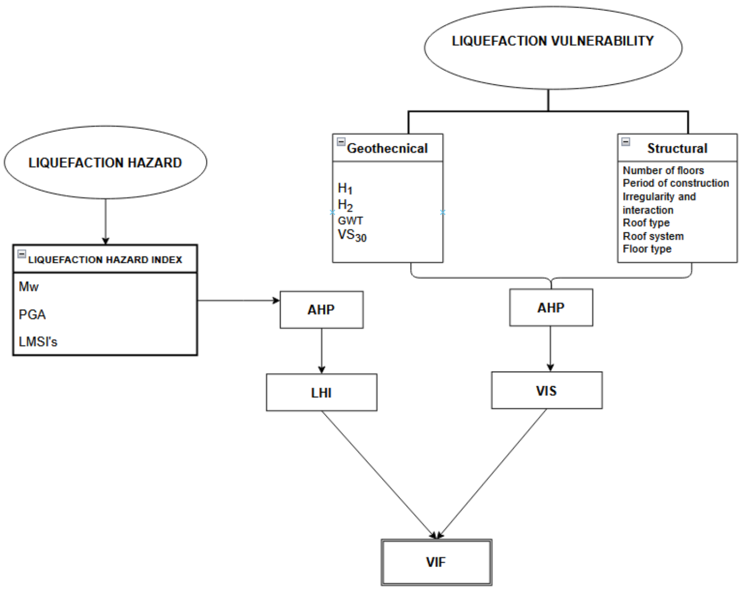

Fig. 1. Flowchart of the proposed liquefaction vulnerability at an urban scale model.

The identification of the earthquake and liquefaction indicators that exert the most significant influence on the expected vulnerability of the built environment involves extracting from the methodologies existing in the current literature and expert interviews as was done by [11] and adapting them to account for the specific building stock of the study area.

A multi-criteria analysis framework, incorporating the Analytic Hierarchy Process (AHP), is used to assign relative weights to: (i) the selected indicators within each component (denoted as p_i); and (ii) the corresponding scores for each class (denoted as S_i). Each indicator (denoted as n) is classified into classes representing its relative impact on the physical vulnerability of the built environment to liquefaction.

The LHI and the VIS are obtained by:

$$LHI, VIS = \sum_{i}^{n} S_i . p_i \tag{1}$$

Once the LHI and the VIS are obtained, the integrated VIF is obtained by:

$$VIF = VIS \times (1 + PL \times LHI) \tag{2}$$

where PL is the probability of liquefaction varies between 0 and 1. Equation 2 integrates LHI and VIS into the VIF. More details of the PL term for urban centres assessments could be found in [12]. The term $(1 + \mathrm{PL} \times \mathrm{LHI})$ ensures that higher LHI and the PL amplify the structural vulnerability, while buildings with low VIS are less affected by increased liquefaction hazard.

The proposed methodology will be validated in a place affected by earthquake-induced liquefaction and subsequent damage to the built environment. The validation is conducted in Christchurch, New Zealand, a city that experienced significant liquefaction during multiple seismic events.

To achieve this, a high-resolution digital dataset containing approximately 14,500–15,500 CPT-based case histories has been compiled from three significant earthquake events in Canterbury: the September 2010 (M_w 7.1); February 2011 (M_w 6.2), and February 2016 (M_w 5.7) earthquakes [13].

These datasets provide critical insights into surface liquefaction manifestations, especially in cases where a non-liquefiable layer overlays a liquefiable one, a common condition in the study area. Although these datasets do not include direct structural damage information, they help establish correlations between LMSI and built environment vulnerability. This validation step refines weighting factors within the proposed methodology, improving its accuracy and reliability.

3 CASE OF STUDY: AGUABLANCA DISTRICT, CALI, COLOMBIA

After the proposed methodology is validated, the methodology will be applied in Commune 21, located within the Aguablanca District (AD) in Cali, Colombia (Fig. 2). This region lies on the western floodplain of the Cauca River and is characterized by soil deposits with a high to severe susceptibility to liquefaction, as identified in multiple studies [14]–[17]. The presence of a shallow low-permeability layer (non-liquefiable surface layer) followed by unconsolidated and saturated sand may also influence the area's seismic response and requires further investigation [15], [18].

The built environment in the study area primarily consists of non-engineered, low-rise (1-3 stories) unreinforced masonry (URM) buildings with shallow foundations. These structures are particularly vulnerable to liquefaction-induced ground deformations, making AD an ideal case study for assessing seismic risk [17], [19], [20]. Given these characteristics, Commune 21 serves as an optimal case study for applying the proposed methodology.

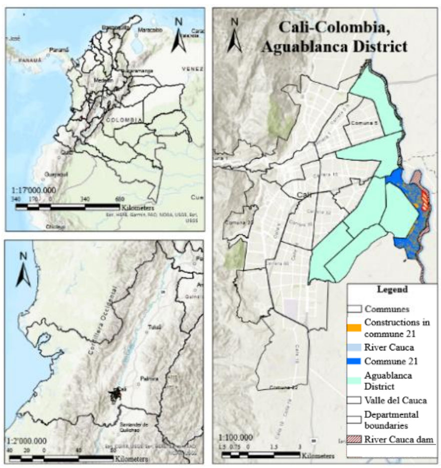

Fig. 2 Study area highlighting Commune 21 in blue.

4 CHALLENGES AND LIMITATIONS

The proposed liquefaction vulnerability model provides a rapid and effective method for assessing liquefaction-induced damage at an urban scale, facilitating targeted risk mitigation efforts. By integrating key geotechnical, structural, and seismic indicators, this framework enhances informed decision-making in urban planning for seismically active regions.

This methodology is part of a four-year research project, and its application to the case study is currently in progress. A VIS has already been developed for the study area, considering structural vulnerability indicators. However, the soil and foundation components still need to be incorporated. Given the level of detail required for an urban-scale assessment, foundations are excluded as a vulnerability parameter in this study.

A key challenge of this research is the development of vulnerability curves, which relate the VIF to different levels of seismic demand. These curves require the definition of damage levels to categorise the structural response of buildings affected by liquefaction-induced ground deformations. According to existing literature, typical damage levels range from slight to severe, with rigid-body displacements, excessive settlements, and tilting being key failure mechanisms [9].

Given that the study area is predominantly composed of non-engineered unreinforced masonry (URM) buildings, the vulnerability curves will be tailored to this building typology. The empirical relationships derived from historical case studies provide a basis for defining threshold values of seismic demand and corresponding damage levels. By incorporating these elements, the model enhances its applicability for urban risk assessments.

Despite its ease of application, the proposed methodology assumes that structures behave as rigid bodies during liquefaction. However, liquefaction can produce complex failure mechanisms, where both inertial forces and soil deformations contribute to building damage. In such cases, the final damage state of a structure is influenced not only by the initial damage from ground shaking but also by subsequent damage induced by liquefaction effects [9].

The notable contribution of this research lies in the inclusion of parameters associated with the vulnerability of residential URM buildings subjected to earthquake-induced liquefaction.

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6 REFERENCES

[1] H.-S. Kim, "Geospatial data-driven assessment of earthquake-induced liquefaction impact mapping using classifier and cluster ensembles," *Appl. Soft Comput.*, vol. 140, p. 110266, Jun. 2023, doi: 10.1016/j.asoc.2023.110266.

[2] C. Yilmaz, V. Silva, and G. Weatherill, "Probabilistic framework for regional loss assessment due to earthquake-induced liquefaction including epistemic uncertainty," *Soil Dyn. Earthq. Eng.*, vol. 141, p. 106493, Feb. 2021, doi: 10.1016/J.SOILDYN.2020.106493.

[3] G. Bouckovalas and P. Dakoulas, "Liquefaction performance of shallow foundations in presence of a soil crust," in *Geotechnical, Geological and Earthquake Engineering*, vol. 6, Dordrecht: Springer Netherlands, 2007, pp. 245–276. doi: 10.1007/978-1-4020-5893-6_11.

[4] J. D. Bray and J. Macedo, "6th Ishihara lecture: Simplified procedure for estimating liquefaction-induced building settlement," *Soil Dyn. Earthq. Eng.*, vol. 102, pp. 215–231, Nov. 2017, doi: 10.1016/J.SOILDYN.2017.08.026.

[5] S. Dashti, Z. Bullock, K. Porter, A. Liel, and Z. Karimi, "Key predictors of structure settlement on liquefiable ground: a numerical parametric study," *Soil Dyn. Earthq. Eng.*, vol. 113, pp. 286–308, Oct. 2018, doi: 10.1016/J.SOILDYN.2018.03.001.

[6] Z. Bullock, Z. Karimi, S. Dashti, A. Liel, and K. Porter, "Key parameters for predicting residual tilt of shallow-founded structures due to liquefaction," in *Geotechnical Earthquake Engineering and Soil Dynamics V*, Jun. 2018, pp. 425–434. doi: 10.1061/9780784481479.044.
[7] F. A, E. S, V. F, and L. S, "Simplified prediction of settlements of shallow foundations caused by earthquake-induced excess pore water pressures," *Soil Dyn. Earthq. Eng.*, vol. 194, p. 109383, Jul. 2025, doi: 10.1016/j.soildyn.2025.109383.
[8] A. Cruz, N. Chieffo, S. Karimzadeh, E. Sandoval, A. Ortiz, and P. B. Lourenço, "Preliminary simplified approach for the rapid seismic vulnerability assessment of residential unreinforced masonry buildings in urban centres prone to liquefaction," 2024.
[9] J. F. Bird, J. J. Bommer, H. Crowley, and R. Pinho, "Modelling liquefaction-induced building damage in earthquake loss estimation," *Soil Dyn. Earthq. Eng.*, vol. 26, no. 1, pp. 15–30, Jan. 2006, doi: 10.1016/j.soildyn.2005.10.002.
[10] A. Flora *et al.*, "Liquefaction effects in the city of Gölbaşı: from the analysis of predisposing factors to damage survey," *Eng. Geol.*, vol. 338, p. 107633, Aug. 2024, doi: 10.1016/j.enggeo.2024.107633.
[11] A. K. Yildirim, B. Y. Kavus, T. K. Karaca, İ. Bozbey, and A. Taskin, "A novel seismic vulnerability assessment for the urban roadway by using interval valued fermatean fuzzy analytical hierarchy process," *Nat. Hazards*, vol. 120, no. 15, pp. 13811–13834, Dec. 2024, doi: 10.1007/s11069-024-06748-1.
[12] A. Cruz, S. Karimzadeh, N. Chieffo, E. Sandoval, and P. B. Lourenço, "A Review of Probabilistic Approaches for Assessing the Liquefaction Hazard in Urban Areas," *Arch. Comput. Methods Eng.*, vol. 31, no. 8, pp. 4673–4708, Dec. 2024, doi: 10.1007/s11831-024-10124-4.
[13] M. Geyin, B. W. Maurer, B. A. Bradley, R. A. Green, and S. van Ballegooy, "CPT-based liquefaction case histories

compiled from three earthquakes in Canterbury, New Zealand," *Earthq. Spectra*, vol. 37, no. 4, pp. 2920–2945, Nov. 2021, doi: 10.1177/8755293021996367.

[14] S. Arango-Serna, L. Gallo, J. Zambrano, E. Sandoval-Vallejo, A. Cruz, and P. Thomson, "New seismic monitoring center to assess the liquefaction risk posed by subduction earthquakes," *J. Seismol.*, 2023.

[15] S. Arango-Serna, M. Herrera, A. Cruz, E. Sandoval, P. Thomson, and C. Ledezma, "Use of ambient noise records in seismic engineering: An approach to identify potentially liquefiable sites," *Soil Dyn. Earthq. Eng.*, vol. 148, p. 106837, Sep. 2021, doi: 10.1016/j.soildyn.2021.106837.

[16] Ingeominas and DAGMA, "Estudio de microzonificación sísmica de Santiago de Cali," Santiago de Cali, 2005.

[17] R. Styron, C. Yepes-Estrada, and V. Silva, "Earthquake-induced landslides and liquefaction in Cali, Colombia. GEM-TREQ project technical report," 2022.

[18] E. Sandoval-Vallejo, W. Campaña-Diaz, and A. Cruz-Escobar, "Liquefaction resistance of Aguablanca terrigenous sand in Santiago de Cali," *DYNA*, vol. 80, no. 181, 2013.

[19] A. B. Acevedo *et al.*, "Seismic risk assessment for the residential buildings of the major three cities in Colombia: Bogotá, Medellín, and Cali," *Earthq. Spectra*, vol. 36, no. 1_suppl, pp. 298–320, Oct. 2020, doi: 10.1177/8755293020942537.

[20] C. Yepes - Estrada, A. B. Acevedo, J. Arenas, H. Pérez, A. Calderón, and D. González-González, "Exposure model for catastrophic risk assessment of Santiago de Cali, Colombia," 2022.